The CRESST Dark Matter Search

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Abstract. We present the current status of CRESST (Cryogenic Rare Event Search using Superconducting Thermometers) project and new results concerning detector development. The basic technique involved is to search for WIMPs by the measurement of non-thermal phonons, as created by WIMP-induced nuclear recoils. Combined with our newly developed method for the simultaneous measurement of scintillation light, strong background discrimination is possible, resulting in a substantial increase in WIMP detection sensitivity.

1 CRESST and the Dark Matter Problem

After a long period of development, cryogenic detectors are now coming on line and deliver significant results in particle-astrophysics and weak interactions. The goal of the CRESST project is the direct detection of elementary particle dark matter and the elucidation of its nature. Particle physics provides a well motivated dark matter candidate through the lightest supersymmetric (SUSY) particle, the 'neutralino' and one can find candidates in a wide mass range [1]. Generically, such particles are called WIMPS (Weakly Interacting Massive Particles). WIMPS are expected to interact with ordinary matter by elastic scattering on nuclei. Conventional methods for direct detection rely on the ionization or scintillation caused by the recoiling nucleus. This leads to limitations connected with the relatively high energy involved in producing electron-hole pairs. Cryogenic detectors use the much lower energy excitations, such as phonons. Since the principal physical effect of a WIMP nuclear recoil is the generation of phonons, cryogenic calorimeters are well suited for WIMP detection. Further, when this technology is combined with charge or light detection the resulting background suppression leads to a powerful technique to search for the rare nuclear recoils.

The detectors developed by the CRESST collaboration consist of a dielectric target-crystal with a small superconducting film evaporated onto the surface. When this film is held at a temperature in the middle of its superconducting to normal conducting phase transition, it functions as a highly sensitive thermometer. The detectors presently employed in Gran Sasso use tungsten (W) films and sapphire (Al_2O_3) absorbers, running near 15 mK. The technique can

also be applied to a variety of other materials. The small change in temperature of the superconducting film resulting from an energy deposit in the target leads to a relatively large change in the film's resistance. This change in resistance is measured with a SQUID. A small separate detector of the same type is used to see the light emitted when the target is a scintillating crystal.

2 Present Status of CRESST

The task set for the first stage of CRESST was to show the operation of four 262 g sapphire detectors, with a threshold of 500 eV under low background conditions. Meeting this goal involved the setting up of a low background, large volume, cryogenic installation and the development of massive, low background detectors with low energy thresholds.

The central part of the CRESST installation at the LNGS is the cryostat. The cryostat design separates the detectors in the "cold box" from the dilution refrigerator by a 1.5 m long "cold finger", with internal cold lead shielding blocking the line-of-sight to the detectors. The cold box is constructed entirely of low background materials, without any compromise. It is surrounded by shielding consisting of 20 cm of lead and 14 cm of copper. The volume for the detectors of about 30 l is large enough to use much larger detectors in the future. The cold box and shielding are installed in a clean room area with a measured clean room class of 100. For servicing, the top of the cryostat can be accessed from the first floor outside the clean room.

The installation was completed at Gran Sasso in 1997 and a series of detector tests were made in the prototype cold box during 1998. The purpose of the prototype cold box was to test the mechanical and cryogenic functioning of the design and to provide a reasonably shielded environment for completing the development of the 262 g sapphire detectors. As can be expected in such a complicated setup, the first runs showed that several details needed improvement: Vibrations caused by the needle valve of the dilution refrigerator's 1 K pot needed to be eliminated by installing a fixed impedance; the design of the detector holders needed to be improved to reduce the vibrational effect of the boiling of the liquid nitrogen; the slow heat release due to enclosed H2 in the Cu of some new components needed to be understood and eliminated by carefully selecting low background Cu which does not have this problem.

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At the end of this testing periods we had four 262 sapphire detectors which achieved energy resolutions in the range of 200 eV (FWHM) at 1.5 keV. The best detector reached a resolution of 133 eV at 1.5 keV. The spectrum is shown in fig. 1. As mentioned above, these tests were made in the prototype cold box, which was made of the right type of copper but which had been exposed at the

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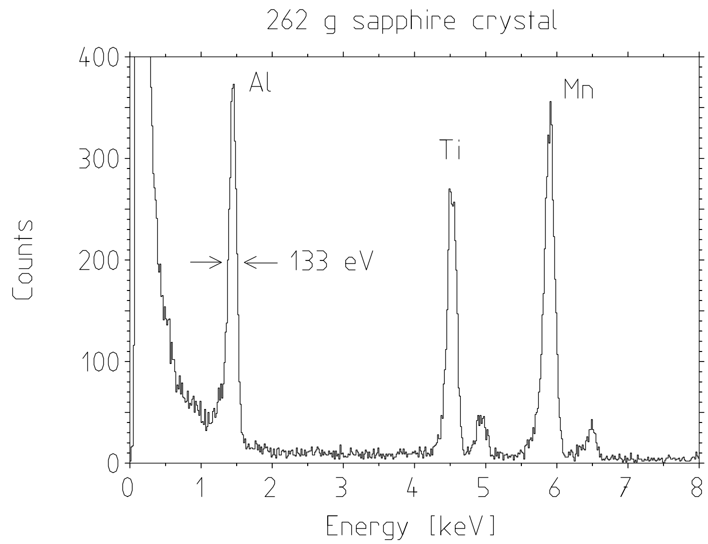

Fig. 1. Low energy X-ray spectrum from one of the 262gr Sapphire-detectors. The energy resolution at 1keV is 133eV FWHM. The energy threshold is below 500eV. The rise in countrate at low energies is due to Auger electrons.

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shape of the measured energy spectra. Moreover, the rate had a nonpoissonian character in time, which can not be caused by radioactivity.

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After having excluded radioactivity, vibrations and electronic interference as the source of the background, a remaining possibility was that the energy depositions in the crystals are due to random structural relaxation in the supporting structure of the crystal. This possibility was investigated in spring 2000. The sapphire spheres, supporting the absorber crystal, were replaced by small Teflon mounts. This way the contact surface of the crystal to its holders was enlarged and the pressure reduced. This measure resulted in a significant reduction of the background rate. For energies from 15 keV to 25 keV the rate is now below 1 count / (kg keV day), which is in the range we are aiming for. At lower energies the rate is dominated by a line at 8keV, presumably the K_α X-ray line of Copper. We are confident of being able to present results on Dark Matter during the year 2000.

3 The new Detectors

If all disturbances are removed, the remaining background will be dominated by β and γ emissions from nearby radioactive contaminants. These produce exclusively electron recoils in the detector. Therefore, dramatic improvements in sensitivity are to be expected if the detector itself is capable of distinguishing

electrons from nuclear recoils and rejecting them. We have recently developed a system, presently using $CaWO_4$ crystals as the absorber, where a measurement of scintillation light is carried out in parallel to the phonon detection. We find that these devices clearly discriminate nuclear recoils from electron recoils.

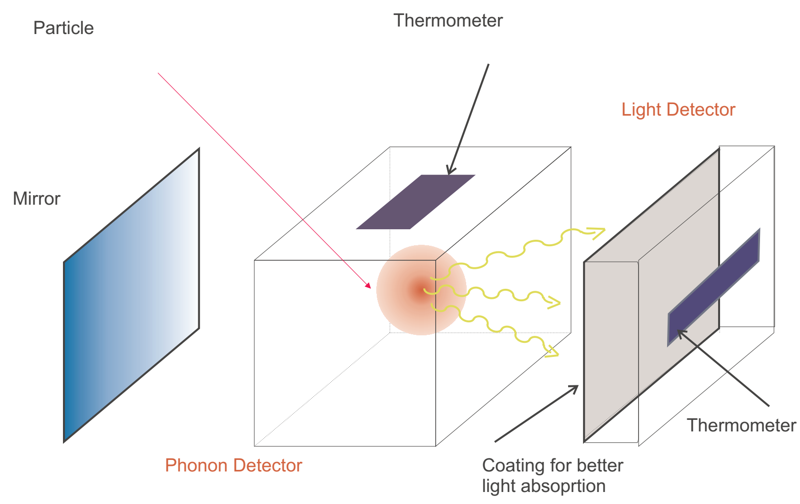

Fig. 2. Schematic view of the arrangement used for the simultaneous light and phonon detection. A second smaller calorimeter next to the absorber is used to measure the scintillation light. Mirrors or a reflective coating on the inside of the detector holders improve the light collection efficiency. The light detector is coated for better light absorption.

We first studied the light output of several intrinsic scintillating crystals. Al crystals tested so far (BGO, BaF_2, $PbWO_4$, $CaWO_4$) showed adequate light output at mK temperatures. The high sensitivity of the W phase transition thermometers allows us to use a small cryogenic calorimeter to measure the light emitted from a scintillating absorber crystal. To demonstrate the detection principle we developed a test detector consisting of a scintillating $CaWO_4$ absorber with a mass of 6 g and a separate light detector. Both the absorber and the light detector were instrumented with their own tungsten superconducting phase transition thermometer operating at about 12mK. The system is shown schematically in fig. 2 . It consists of two independent detectors: A scintillating absorber with a superconducting phase transition thermometer on it, and a similar but smaller detector placed next to it to detect the scintillation light from the first detector. A detailed description is given in [2]. With this device we succeeded to simultaneously measure the phonons and the scintillation light from particle interactions in the $CaWO_4$ absorber. The detector was irradiated with γ-rays and electrons. Adding an external neutron source we could demonstrate clear discrimination between electron and nuclear recoils.

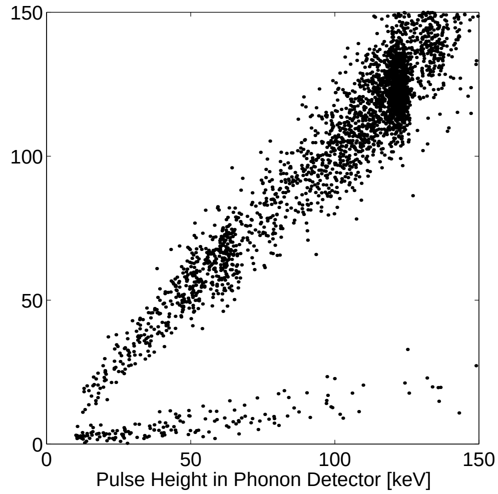

Fig. 3. Pulse height in the light detector versus pulse height in the phonon detector. The scatter plot has been measured with an electron-, a photon-, and a neutron source. The upper line corresponds to electron recoils, the lower to nuclear recoils. On can clearly discriminate the two down to energies of about 10keV.

Figure 3 shows a scatter plot of the pulse heights observed in the light detector versus the pulse height observed in the phonon detector. A clear correlation between the light and phonon signals is observed. A second line can be seen due to nuclear recoils induced by neutrons from an Americium-Beryllium source. It is to be observed that electron and nuclear recoils can be clearly distinguished down to a threshold of 10keV. A detailed evaluation yields a background rejection factor of 98% in the energy range between 10 keV and 20 keV, 99.7% in the range between 15 keV and 25 keV and better than 99.9% above 20 keV.

In Munich we are presently working on the development of a 300 g $CaWO_4$ prototype detector. We recently demonstrated a good light collection with such a 300 g crystal, sufficient to realize a prototype detector for Gran Sasso. We plan to install such a 300 g detector this year in Gran Sasso. Projections indicate that this step would move CRESST from its good sensitivity to low mass dark matter WIMPs with the sapphire detectors to a position where it can compete favorably in the higher mass regime with the best proposed experiments.

4 Next Steps for CRESST

Due to the complementary detector concepts of low threshold calorimeters on the one hand and detectors with the simultaneous measurement of light and phonons on the other, CRESST can cover a very wide range of WIMP masses. The present sapphire detectors, with their extremely low energy thresholds and a low mass

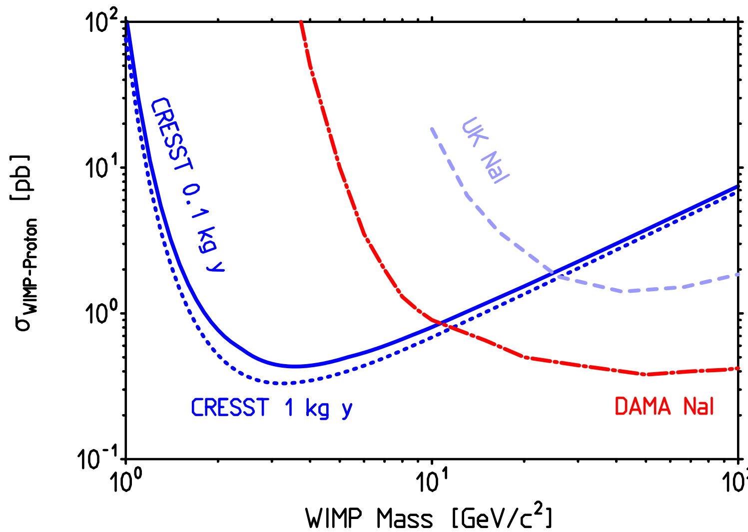

Fig. 4. Equivalent WIMP-proton cross section limits (90% CL) for spin dependent interactions as a function of the WIMP-mass, as expected for the present CRESST sapphire detectors with a total mass of 1 kg. The expectation is based on a threshold of 0.5 keV, a background of 1 count/(kg keV day) and an exposure of 0.1 and 1 kg year. For comparison the present limits from the DAMA [4] and UKDMC [5] NaI experiments are also shown.

target nucleus with high spin (Al), cover the low WIMP mass range from 1 GeV to 10 GeV in the sense that they are presently the only detector type able to explore this mass range effectively. Besides CRESST, also the ROSEBUD-Collaboration is running very similar cryogenic sapphire detectors [3]. Data-taking with the present sapphire (Al_2O_3) detectors (262 g each) will continue during 2000. Possible limits for spin dependent interaction are shown in fig. 4.

The detectors with background suppression using the simultaneous measurement of scintillation light and phonons will have target nuclei of large atomic number, such as tungsten, making them particularly sensitive to WIMPs with coherent interactions and higher mass above about 20GeV. In 2000 we intend the first installation of this next detector generation at Gran Sasso. A 60 GeV WIMP with the cross section claimed in [6] would give about 55 counts between 15 and 25 keV in 1 kg $CaWO_4$ within one year. A background of 1 count/(kg keV day) suppressed with 99.7% would leave 11 background counts in the same energy range. A 1 kg $CaWO_4$ detector with 1 year of measuring time in the present setup of CRESST should thus allow a comfortable test of the reported positive signal as shown in fig 5.

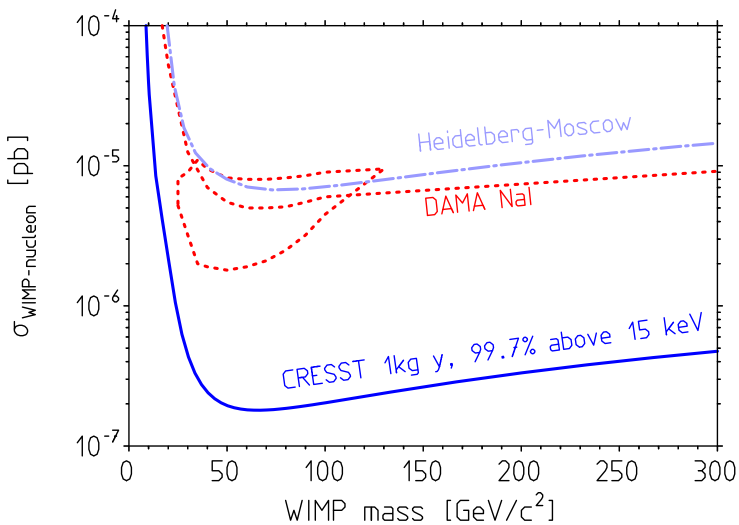

Fig. 5. WIMP-nucleon cross section limits (90% CL) for scalar (coherent) interactions as a function of the WIMP mass, expected for a 1 kg $CaWO_4$ detector with a background rejection of 99.7% above a threshold of 15 keV detector and 1 year of measurement time in the CRESST set-up in Gran Sasso. For comparison the limit from the Heidelberg-Moscow ^{76}Ge experiment [7] and the DAMA NaI limits [4] (with the contour for positive evidence [6]) is also shown.

5 Long Term Perspectives

After successful implementation of the first $CaWO_4$ detectors we intend to upgrade the multichannel SQUID read out and systematically increase the detector mass, which can go up to about 100 kg .

With a 100 kg $CaW0_4$ detector and a background level of 1count/kg/kev/day, the sensitivity shown in fig. 6 can be reached in one year of measuring time. If we wish to cover most of the MSSM parameter space of SUSY with neutralino dark matter, the exposure would have to be increased to about 300 kg years, the background suppression improved to about 99.99 % above 15 keV, and the background lowered to 0.1 count/(kg keV day). The recent tests in Munich with $CaWO_4$, which were limited by ambient neutrons, suggest that a suppression factor of this order should be within reach underground, with the neutrons well shielded and employing a muon veto.

If WIMPs are not found, at some point the neutron flux, which also gives nuclear recoils, will begin to limit further improvement. With careful shielding the neutron flux in Gran Sasso should not limit the sensitivity within the expo-

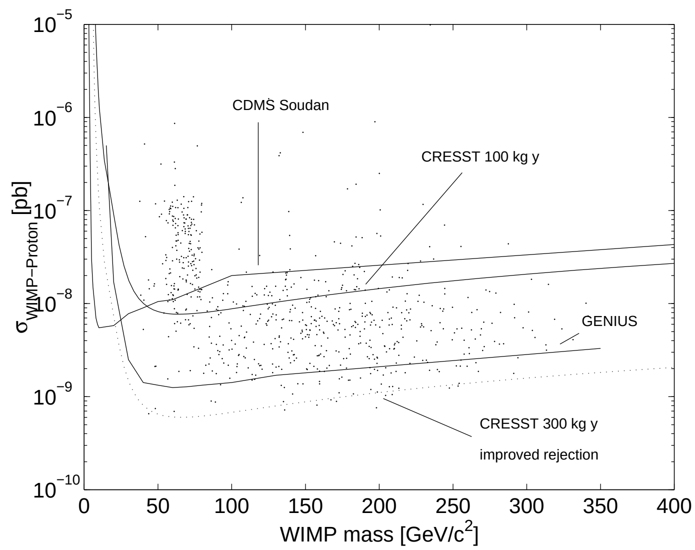

Fig. 6. WIMP-nucleon cross section limits (90% CL) for coherent interactions, as a function of the WIMP mass, expected for a $CaWO_4$ detector with a background of 1 count/(keV kg day) , a background suppression of 99.9% above a threshold of 15 keV, and an exposure of 100 kg-years in the CRESST setup. With a suppression of 99.99% above 15 keV, a reduced background of 0.1 counts/(kg keV day), and an increased exposure of 300 kg years most of the MSSM parameter space would be covered. For comparison, the projected sensitivity of CDMS at Soudan [8], and of the GENIUS experiment [9] are also shown. All sensitivities are scaled to a galactic WIMP density of 0.3 GeV/cm^3. The dots represent expectations for WIMP-neutralinos calculated in the MSSM framework with non-universal scalar mass unification [10].

sures assumed for the upper CRESST curve in fig. 6. With still larger exposures, the neutron background may still be discriminated against large mass WIMPS. This can be done by comparing different target materials, which is possible with the CRESST technology, since different variations with nuclear number for the recoil spectra are to be expected with different mass projectiles.

6 Conclusions

The installation of the large volume, low background, cryogenic facility of CRESST at the Gran Sasso Laboratory is completed. The highly sensitive CRESST sapphire will allow to explore the low mass WIMP range. The new detectors with the simultaneous measurement of phonons and scintillation light allow to distinguish the nuclear recoils very effectively from the electron recoils caused by background radioactivity. For medium and high mass WIMPs this results in one of the highest sensitivities possible with today's technology. The excellent background suppression of cryodetectors with active background rejection makes

them much less susceptible to systematic uncertainties than conventional detectors, which must rely heavily on a subtraction of radioactive backgrounds. Since this kind of systematic uncertainty cannot be compensated by an increase of detector mass, even moderate sized cryogenic detectors can achieve much better sensitivity than large mass conventional detectors.

7 Acknowledgement

This work was supported by the "SFB 375-95 für Astro-Teilchenphysik der DFG and the EU research network contract number FMRX-CT98-0167 (DG12-MIHT).

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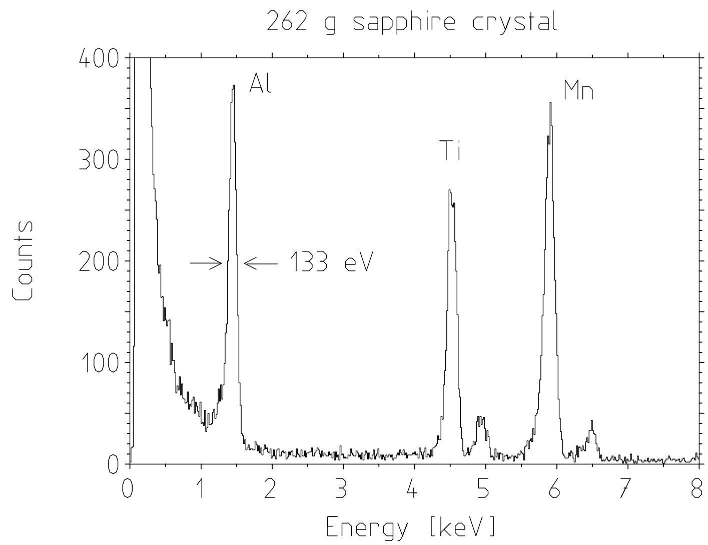

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electrons from nuclear recoils and rejecting them. We have recently developed a system, presently using $CaWO_4$ crystals as the absorber, where a measurement of scintillation light is carried out in parallel to the phonon detection. We find that these devices clearly discriminate nuclear recoils from electron recoils.

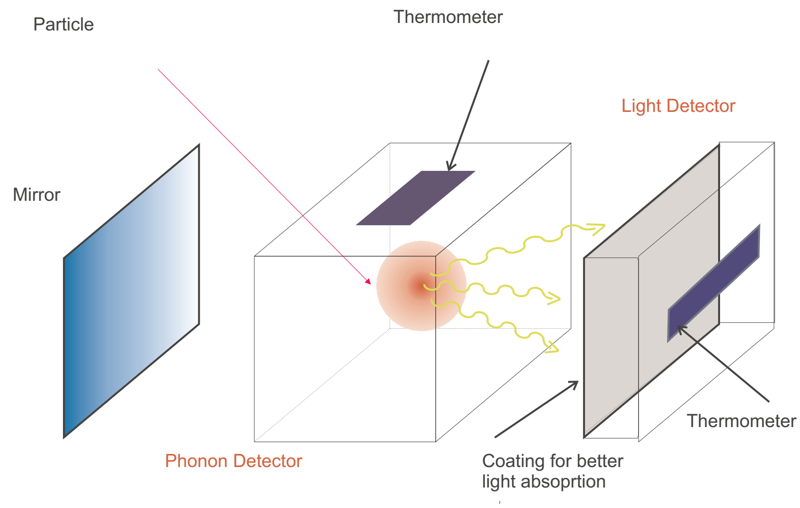

Fig. 2. Schematic view of the arrangement used for the simultaneous light and phonon detection. A second smaller calorimeter next to the absorber is used to measure the scintillation light. Mirrors or a reflective coating on the inside of the detector holders improve the light collection efficiency. The light detector is coated for better light absorption.

We first studied the light output of several intrinsic scintillating crystals. Al crystals tested so far (BGO, BaF_2, $PbWO_4$, $CaWO_4$) showed adequate light output at mK temperatures. The high sensitivity of the W phase transition thermometers allows us to use a small cryogenic calorimeter to measure the light emitted from a scintillating absorber crystal. To demonstrate the detection principle we developed a test detector consisting of a scintillating $CaWO_4$ absorber with a mass of 6 g and a separate light detector. Both the absorber and the light detector were instrumented with their own tungsten superconducting phase transition thermometer operating at about 12mK. The system is shown schematically in fig. 2 . It consists of two independent detectors: A scintillating absorber with a superconducting phase transition thermometer on it, and a similar but smaller detector placed next to it to detect the scintillation light from the first detector. A detailed description is given in [2]. With this device we succeeded to simultaneously measure the phonons and the scintillation light from particle interactions in the $CaWO_4$ absorber. The detector was irradiated with γ-rays and electrons. Adding an external neutron source we could demonstrate clear discrimination between electron and nuclear recoils.

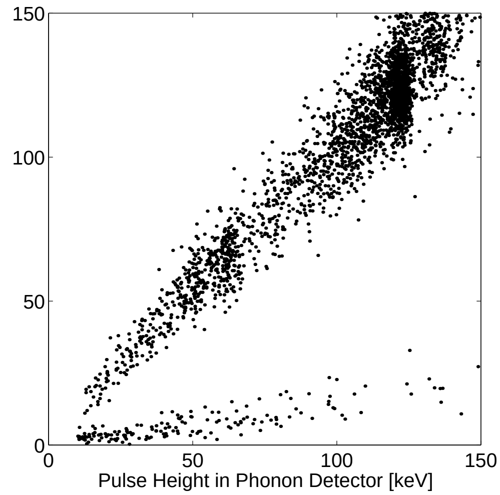

Fig. 3. Pulse height in the light detector versus pulse height in the phonon detector. The scatter plot has been measured with an electron-, a photon-, and a neutron source. The upper line corresponds to electron recoils, the lower to nuclear recoils. On can clearly discriminate the two down to energies of about 10keV.

Figure 3 shows a scatter plot of the pulse heights observed in the light detector versus the pulse height observed in the phonon detector. A clear correlation between the light and phonon signals is observed. A second line can be seen due to nuclear recoils induced by neutrons from an Americium-Beryllium source. It is to be observed that electron and nuclear recoils can be clearly distinguished down to a threshold of 10keV. A detailed evaluation yields a background rejection factor of 98% in the energy range between 10 keV and 20 keV, 99.7% in the range between 15 keV and 25 keV and better than 99.9% above 20 keV.

In Munich we are presently working on the development of a 300 g $CaWO_4$ prototype detector. We recently demonstrated a good light collection with such a 300 g crystal, sufficient to realize a prototype detector for Gran Sasso. We plan to install such a 300 g detector this year in Gran Sasso. Projections indicate that this step would move CRESST from its good sensitivity to low mass dark matter WIMPs with the sapphire detectors to a position where it can compete favorably in the higher mass regime with the best proposed experiments.

4 Next Steps for CRESST

Due to the complementary detector concepts of low threshold calorimeters on the one hand and detectors with the simultaneous measurement of light and phonons on the other, CRESST can cover a very wide range of WIMP masses. The present sapphire detectors, with their extremely low energy thresholds and a low mass

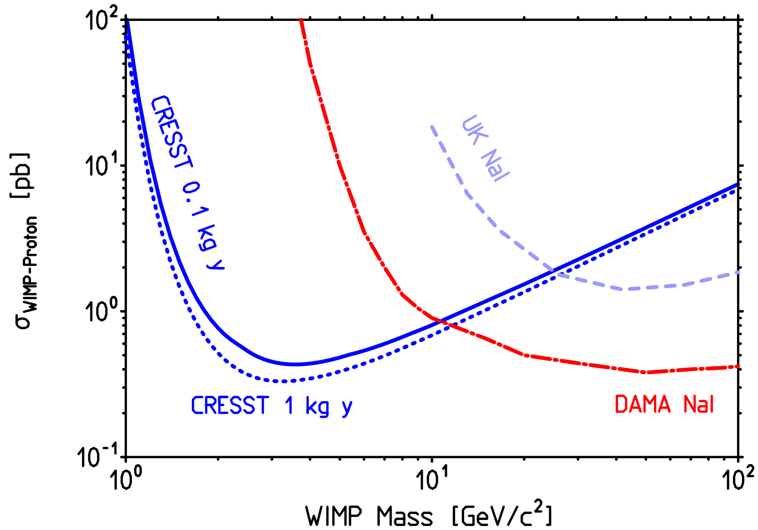

Fig. 4. Equivalent WIMP-proton cross section limits (90% CL) for spin dependent interactions as a function of the WIMP-mass, as expected for the present CRESST sapphire detectors with a total mass of 1 kg. The expectation is based on a threshold of 0.5 keV, a background of 1 count/(kg keV day) and an exposure of 0.1 and 1 kg year. For comparison the present limits from the DAMA [4] and UKDMC [5] NaI experiments are also shown.

target nucleus with high spin (Al), cover the low WIMP mass range from 1 GeV to 10 GeV in the sense that they are presently the only detector type able to explore this mass range effectively. Besides CRESST, also the ROSEBUD-Collaboration is running very similar cryogenic sapphire detectors [3]. Data-taking with the present sapphire (Al_2O_3) detectors (262 g each) will continue during 2000. Possible limits for spin dependent interaction are shown in fig. 4.

The detectors with background suppression using the simultaneous measurement of scintillation light and phonons will have target nuclei of large atomic number, such as tungsten, making them particularly sensitive to WIMPs with coherent interactions and higher mass above about 20GeV. In 2000 we intend the first installation of this next detector generation at Gran Sasso. A 60 GeV WIMP with the cross section claimed in [6] would give about 55 counts between 15 and 25 keV in 1 kg $CaWO_4$ within one year. A background of 1 count/(kg keV day) suppressed with 99.7% would leave 11 background counts in the same energy range. A 1 kg $CaWO_4$ detector with 1 year of measuring time in the present setup of CRESST should thus allow a comfortable test of the reported positive signal as shown in fig 5.

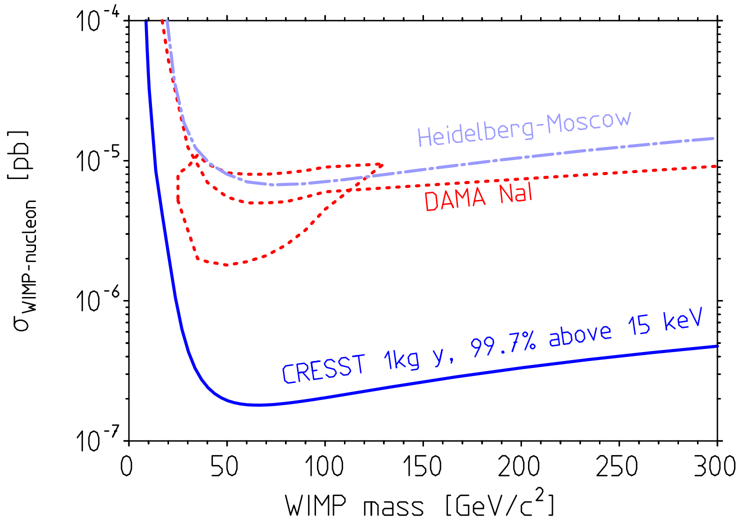

Fig. 5. WIMP-nucleon cross section limits (90% CL) for scalar (coherent) interactions as a function of the WIMP mass, expected for a 1 kg $CaWO_4$ detector with a background rejection of 99.7% above a threshold of 15 keV detector and 1 year of measurement time in the CRESST set-up in Gran Sasso. For comparison the limit from the Heidelberg-Moscow ^{76}Ge experiment [7] and the DAMA NaI limits [4] (with the contour for positive evidence [6]) is also shown.

5 Long Term Perspectives

After successful implementation of the first $CaWO_4$ detectors we intend to upgrade the multichannel SQUID read out and systematically increase the detector mass, which can go up to about 100 kg .

With a 100 kg $CaW0_4$ detector and a background level of 1count/kg/kev/day, the sensitivity shown in fig. 6 can be reached in one year of measuring time. If we wish to cover most of the MSSM parameter space of SUSY with neutralino dark matter, the exposure would have to be increased to about 300 kg years, the background suppression improved to about 99.99 % above 15 keV, and the background lowered to 0.1 count/(kg keV day). The recent tests in Munich with $CaWO_4$, which were limited by ambient neutrons, suggest that a suppression factor of this order should be within reach underground, with the neutrons well shielded and employing a muon veto.

If WIMPs are not found, at some point the neutron flux, which also gives nuclear recoils, will begin to limit further improvement. With careful shielding the neutron flux in Gran Sasso should not limit the sensitivity within the expo-

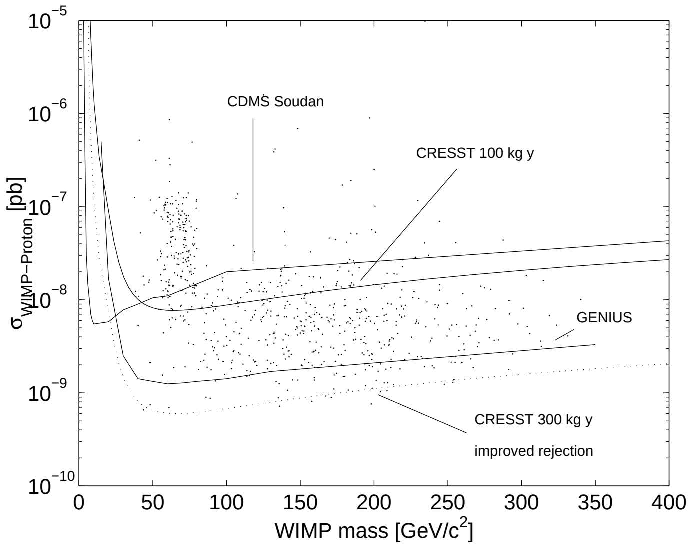

Fig. 6. WIMP-nucleon cross section limits (90% CL) for coherent interactions, as a function of the WIMP mass, expected for a $CaWO_4$ detector with a background of 1 count/(keV kg day) , a background suppression of 99.9% above a threshold of 15 keV, and an exposure of 100 kg-years in the CRESST setup. With a suppression of 99.99% above 15 keV, a reduced background of 0.1 counts/(kg keV day), and an increased exposure of 300 kg years most of the MSSM parameter space would be covered. For comparison, the projected sensitivity of CDMS at Soudan [8], and of the GENIUS experiment [9] are also shown. All sensitivities are scaled to a galactic WIMP density of 0.3 GeV/cm^3. The dots represent expectations for WIMP-neutralinos calculated in the MSSM framework with non-universal scalar mass unification [10].

sures assumed for the upper CRESST curve in fig. 6. With still larger exposures, the neutron background may still be discriminated against large mass WIMPS. This can be done by comparing different target materials, which is possible with the CRESST technology, since different variations with nuclear number for the recoil spectra are to be expected with different mass projectiles.

6 Conclusions

The installation of the large volume, low background, cryogenic facility of CRESST at the Gran Sasso Laboratory is completed. The highly sensitive CRESST sapphire will allow to explore the low mass WIMP range. The new detectors with the simultaneous measurement of phonons and scintillation light allow to distinguish the nuclear recoils very effectively from the electron recoils caused by background radioactivity. For medium and high mass WIMPs this results in one of the highest sensitivities possible with today's technology. The excellent background suppression of cryodetectors with active background rejection makes

them much less susceptible to systematic uncertainties than conventional detectors, which must rely heavily on a subtraction of radioactive backgrounds. Since this kind of systematic uncertainty cannot be compensated by an increase of detector mass, even moderate sized cryogenic detectors can achieve much better sensitivity than large mass conventional detectors.

7 Acknowledgement

This work was supported by the “SFB 375-95 für Astro-Teilchenphysik der DFG and the EU research network contract number FMRX-CT98-0167 (DG12-MIHT).

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